# Imaging Salt Dome Flank and Dipping Sediments using Time Reversed Acoustics

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## Abstract

In this paper we define the theory and basic principles to move (redatum) the surface shots from a walk away VSP to be as if they had been located in the borehole. We will refer to this theory using several of the terms used in the literature including Time Reverse Acoustics (TRA), Seismic Interferometry (SI) and Virtual Source (VS) technology. Regardless of the name, the theory is built upon reciprocity and the time symmetry of the wave equation. We apply these TRA principles, together with prestack depth migration, to produce images of a modeled salt dome flank. We create a set of synthetic traces representing a multi-level, walk away VSP for a model composed of a simplified Gulf of Mexico vertical velocity gradient and an embedded overhanging salt dome. The sediment reflectors in the model dip up towards the salt dome flank. The energy from the surface shots is bent into turning rays by the linear $v(z)$ gradient which illuminate the steeply dipping sediments and overhanging salt edges. The illuminating energy is reflected and scattered from these surfaces and then captured by the downhole VSP receivers. To simplify the processing of these data, we move (redatum) the surface shots into the borehole using our TRA or seismic interferometry principles. This removes from the seismic traces the entire, potentially complicated, path from the surface shot location to the borehole without having to perform any velocity analyses or moveout corrections. Each of these new (redatummed) traces mimics the output of a down-hole source and down-hole receiver pair. We apply prestack depth migration to these new traces to produce the final image of the beds and the salt dome flank which agree very well with the original model structure.

## 1. Introduction

In physical Time Reverse Acoustic experiments, the wavefield from a source in a medium is measured on a boundary surrounding that medium. The recorded wavefield is time reversed and sent back into the medium from the locations of the original recordings. The result of such an experiment is that the wavefield collapses (retro-focuses) back at the location of the source (Fink, 1999). If the measurements are made on only part of the boundary, then the geometry corresponds to what is called a Time Reversal Mirror (TRM) in the literature. In a walk-away VSP the geometry is not naturally the same as in a TRA experiment since we cannot form a contour of sources (or receivers) which completely enclose the borehole. Since the sources are on the surface and the receivers are in the borehole, we invoke reciprocity to exchange the sources and receivers. After this exchange, the geometry mimics a reverse VSP (RVSP) with a collection of shot gathers from downhole sources and many receivers on part of an enclosing contour. With this data set it is straight forward to apply the retro-focusing concepts of TRA and TRM.

Willis *et al.* (2005, 2006) apply these principles to the imaging of a salt-dome flank using Vertical Seismic Profiling (VSP) data. By summing the autocorrelations of traces recorded in the borehole due to sources at the surface, they create a zero-offset section as if it were acquired with coincident source and receiver pairs in the borehole. Essentially, the correlation-and-summation operation moves (redatums) each of the surface sources into the borehole to the location of each receiver, without having to perform velocity analyses or moveout corrections. This process collapses (retro-focuses) the sources to each receiver location, creating a trace from an effective coincident source and receiver pair in the borehole. They then create an image of the salt dome flank by applying poststack depth migration of these traces from the perspective of the borehole. Just as in surface seismic imaging with turning ray reflections, the efficacy of this method relies on an acquisition geometry which captures the reflected turning-ray energy from the salt-dome flank. Willis *et al.* (2006) conclude that this method can be used effectively in a medium with a $v(z)$ velocity gradient, such as in the Gulf of Mexico (GOM).

The Willis *et al.* (2005, 2006) methodology is a variant of Seismic Interferometry which is being explored by many researchers (e.g. Schuster et al., 2003 and 2004; Bakulin and Calvert, 2004; Calvert *et al.*, 2004; Snieder, 2004; Wapenaar and Fokkema, 2005; Hornby et al., 2006). SI uses the time symmetry of the wave equation together with source-receiver reciprocity to estimate the impulse response between two passive receivers. This allows the estimation of the wavefield that would be observed at one receiver if the other receiver were a source (Wapenaar, 2004). Recent developments in SI (Derode et al., 2003, Wapenaar et al., 2005) have allowed for obtaining novel data sets from traditional recording geometries. Bakulin and Calvert (2004, 2005) have patented a variation of seismic interferometry they call Virtual Source to eliminate the complications from a heterogeneous near subsurface. They show examples for moving (redatumming) surface sources to receivers in a near-horizontal well just beneath the overburden. This may be an excellent way to remove the overburden artifacts on time lapse seismic imaging studies to detect the changes in reservoir properties. Similarly, Hornby et al. (2006) show the results of applying seismic interferometry to obtain an image of a vertical salt dome flank on GOM field data.

In this paper we extend the Willis *et al.* (2005, 2006) methodology for creating downhole, zero offset (poststack) traces to a methodology for creating downhole, non-zero offset (prestack) traces. Just as in surface seismic imaging methods, the migration results using non-zero offset (prestack) data are a big improvement over those using zero offset (poststack) data. This is because the non-zero offset data contain reflections from many different directions allowing a more complete image to be reconstructed. Our results show that the extended methodology creates very good images of the salt flank and sediment layers.

## 2. Theory

**Zero Offset Theory.** In order to create a data set suitable for applying a zero offset time-reversal experiment, we first excite a delta function source of seismic energy and record it at, at least one, and preferably many receivers in the medium. We may then express the wavefield which would have been measured at the original source location, *S*, in terms of the recorded waveforms, as (Derode et al., 2003, Wapenaar and Fokkema, 2005):

$$g_{SS}(t) = \sum_{\forall R} g_{RS}(t) * g_{RS}(-t) \,, \tag{1}$$

where $g_{RS}(t)$ denotes the Green's function measured at a receiver location, *R*, on the TRM from the source at *S* and $g_{RS}(-t)$ denotes its time reversed version. The time-reversal operation consists of taking the recorded signal at one receiver, $g_{RS}(t)$, time reversing it, and reinjecting into the medium at the receiver location, backward through the medium to the source. This can be done simply by convolving the time reversed signal with $g_{RS}(t)$ as the convolutional (Green's function) operator. Because the time-reversed wavefield is injected at the receiver position, one can exploit source-receiver reciprocity which says that the wavefield measured at *R* from a source at *S* is the same as the wavefield measured at *S* from a source at *R*:

$$g_{RS}(t) = g_{SR}(t) \,. \tag{2}$$

Since the convolution of a signal with a time reversed version of itself is mathematically identical to its autocorrelation, the wavefield at the source location, $g_{SS}(t)$, is thus composed of a sum of autocorrelations of recorded wavefield observed at each receiver *R*.

Consider a walk-away VSP geometry with sources at the surface and receivers in the borehole. If we applied the TRA process directly to this data, we would move (redatum) the receivers in the borehole back to the source location at the Earth's surface. This is not our goal. However, we can invoke reciprocity to exchange the source and receivers which creates an effective reverse VSP from our walk away VSP data set. Keeping our original notation, we now want to collapse (retro-focus) the wavefield to the downhole receivers (which are the shots locations in our reverse VSP). Source-receiver reciprocity states that $g_{RS}(-t) = g_{SR}(-t)$. This gives that the wavefield at our reverse VSP shot location (which is the receiver location, *R*, in the original VSP data set) is simply

$$g_{RR}(t) = \sum_{\forall S} g_{RS}(t) * g_{RS}(-t) \,, \tag{3}$$

which is the sum of the autocorrelations of the observed traces.

If instead of a delta function source, we have a conventional band-limited source, denoted as $s(t)$, the zero-offset signal, $h_{RR}(t)$, created by moving (redatumming) the original sources at the surface back to the borehole receiver location, is given as the autocorrelated source wavelet convolved with the actual zero-offset Green's function:

$$h_{RR}(t) = [s(t) * s(-t)] * \sum_{\forall S} g_{RS}(t) * g_{RS}(-t) = AC[s(t)] * g_{RR}(t) . \qquad (4)$$

The representation for $h_{RR}(t)$ only gives kinematically correct results (see Wapenaar and Fokkema, 2005), which is quite acceptable for our application since, for this paper, we are interested in creating an image of the high impedance contrast salt dome flank and surrounding reflectors. So, to obtain one zero-offset trace at the original, downhole receiver location *R*, we auto-correlate all the traces from a VSP common receiver gather and sum them together. A zero-offset section is created by gathering all the autocorrelated and summed common receiver gathers.

**Non-zero Offset Theory.** We extend this methodology to the non-zero-offset case by noting that the wavefield between any two points, *R* and *R'*, in the medium can be obtained with an expression similar to the first expression (Cassereau and Fink, 1992, Derode et al., 2003):

$$g_{RR'}(t) = \sum_{\forall S} g_{RS}(t) * g_{R'S}(-t) . \qquad (5)$$

Simply stated, we can 'manufacture' a set of traces which mimics a downhole source located at one of the receivers locations in the borehole and the corresponding traces recorded at each of the downhole receiver locations for this shot location. We do this by first choosing a pair of downhole receivers. For each surface shot location, we cross correlate the traces for this pair of receivers. We do this for all surface shot locations and sum all of the correlations. This gives us a simulated trace for having a downhole source at one receiver location and the downhole receiver at the other receiver location. We do this for all downhole receiver pairs.

Expression (5) is similar to the Green function representations in Wapenaar and Fokkema (2005) and forms the basis of seismic interferometry. Derode et al. (2003) give an excellent derivation of this expression based on physical arguments. As before, if we consider a bandlimited source function, the new traces all have the autocorrelation of the original source wavelet as the new effective source wavelet. As in equation (4), the new (redatummed) non-zero-offset signal, $h_{RR'}(t)$, contains the autocorrelated source wavelet convolved with the actual non-zero-offset Green's function:

$$h_{RR'}(t) = [s(t) * s(-t)] * \sum_{\forall S} g_{RS}(t) * g_{R'S}(-t) = AC[s(t)] * g_{RR'}(t) \qquad (6)$$

Repeating equation (6) for each combination of down-hole receivers creates the new (redatummed), down-hole common source gather.

## 3. Methodology

We created a 2-D data set representing a multi-level walk away VSP for a model composed of a simplified Gulf of Mexico vertical-velocity gradient and an embedded overhanging salt dome survey. The velocity gradient and values were taken from the EAGE/SEG salt dome model which represents typical GOM velocities. The sources are located at the surface and geophones in the borehole as shown in Figure 1. Five reflectors are introduced on top of the *v*(*z*) gradient as 15%-higher velocity spikes. In this case, the reflectors dip up towards the salt dome flank. Our aim is to image the salt dome flank as well as the dipping reflectors. Accurate determination of the salt/sediment contact can greatly help in reservoir development and reserve estimation.

Our methodology consists of two main steps: 1) moving (redatuming) the shots to the bore hole and 2) imaging the salt dome flank and the reflectors.

The first step is achieved by applying the principles of seismic interferometry to create a new data set consisting of common shot gathers as if the sources were located in the borehole and the receivers were also located in the borehole. Note that the original data consist of common shot gathers with the shots at the surface. We first sort those into common down-hole receiver gathers. Three representative common, down-hole receivers gathers at depths of 2, 3 and 4 km, are shown in Figure 2. These are actual VSP traces and serve as the input data for the seismic interferometry operation.

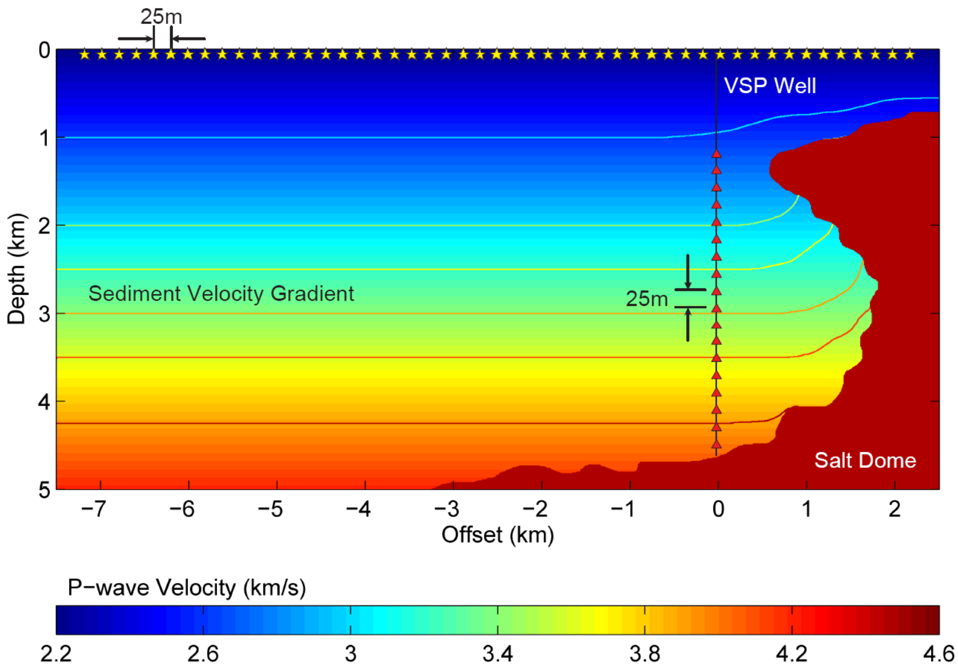


Figure 1: A simplified Gulf of Mexico model of dipping sediments at a salt dome flank with VSP acquisition geometry.

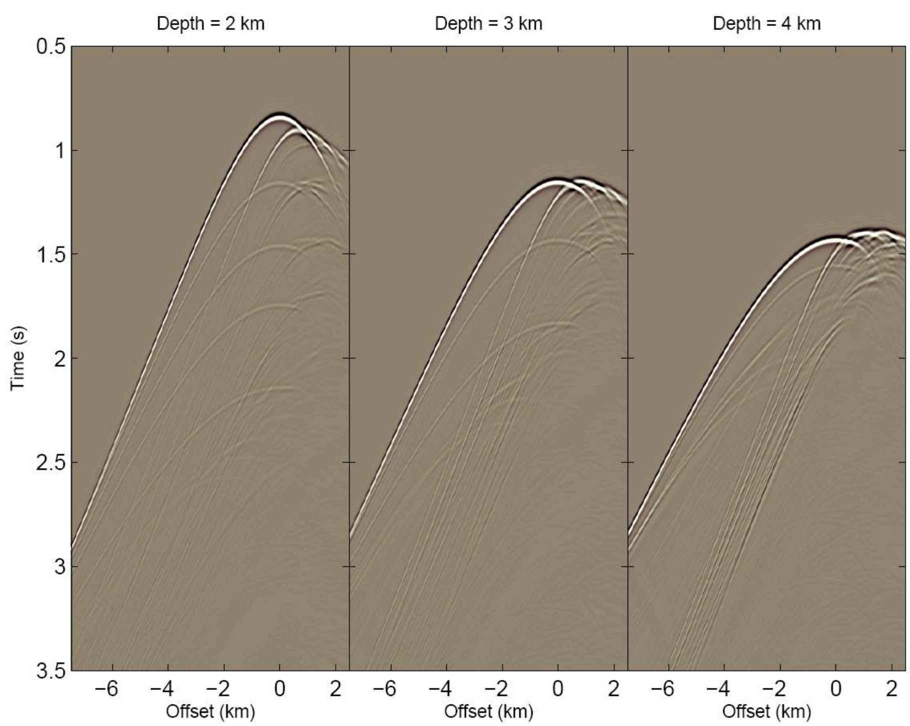


Figure 2: Common down-hole receivers gathers at depths of 2, 3 and 4 km. Sources are at the surface.

The seismic interferometry operation step is then subdivided into several sub-tasks. First we choose one of the actual downhole receiver locations to be a new (redatummed) source location. Then we select another actual downhole receiver location to be a new (redatummed) receiver location. For each actual surface source location, there is a pair of traces corresponding to the actual receiver at the new (redatummed) source location and the actual receiver at the new (redatummed) receiver location. These two traces are cross correlated. For example we could choose the actual source location to be at offset -2000m, the new (redatummed) source to be at depth of 3 km, and the new (redatummed) receiver to be at depth 2 km. We would take the trace at offset -2000m in the middle panel of Figure 2 and cross correlate it with the trace at offset -2000m in the left panel.

The new (redatummed) source and receiver locations are held fixed and this process is repeated for each actual surface shot location. Then all of the correlation traces created by this process are summed together. This single stacked trace becomes the new (redatummed) receiver trace for this set of new (redatummed) source and receiver. In our example above, this new trace is located at a depth of 2 km in the lower panel of Figure 3.

This process is repeated for all new (redatummed) receiver locations for this new (redatummed) source location. This creates a new (redatummed), common down-hole source gather, such as in the lower panel of Figure 3. To obtain a full new (redatummed) down-hole survey, we repeat this for all possible new (redatummed) source locations. Note that for this step we do not have to apply velocity analysis or complicated processing (such as statics or NMO corrections) in order to move (redatum) the shot to be in the borehole. In fact, there are no model dependent processing parameters required to move the surface shots into the borehole.

This procedure gives kinematically correct results (see Wapenaar et al., 2005), which is acceptable for structural imaging applications. For stratigraphic and time-lapse applications more work is needed to insure correct relative amplitudes. In any case, the success of the seismic interferometric redatumming step is determined by how much of energy is reflected off the reflectors near the salt flank and captured by the receivers in the borehole. Because we are trying to image underneath the salt overhang, this is generally only possible in a medium with a $v(z)$ vertical velocity gradient.

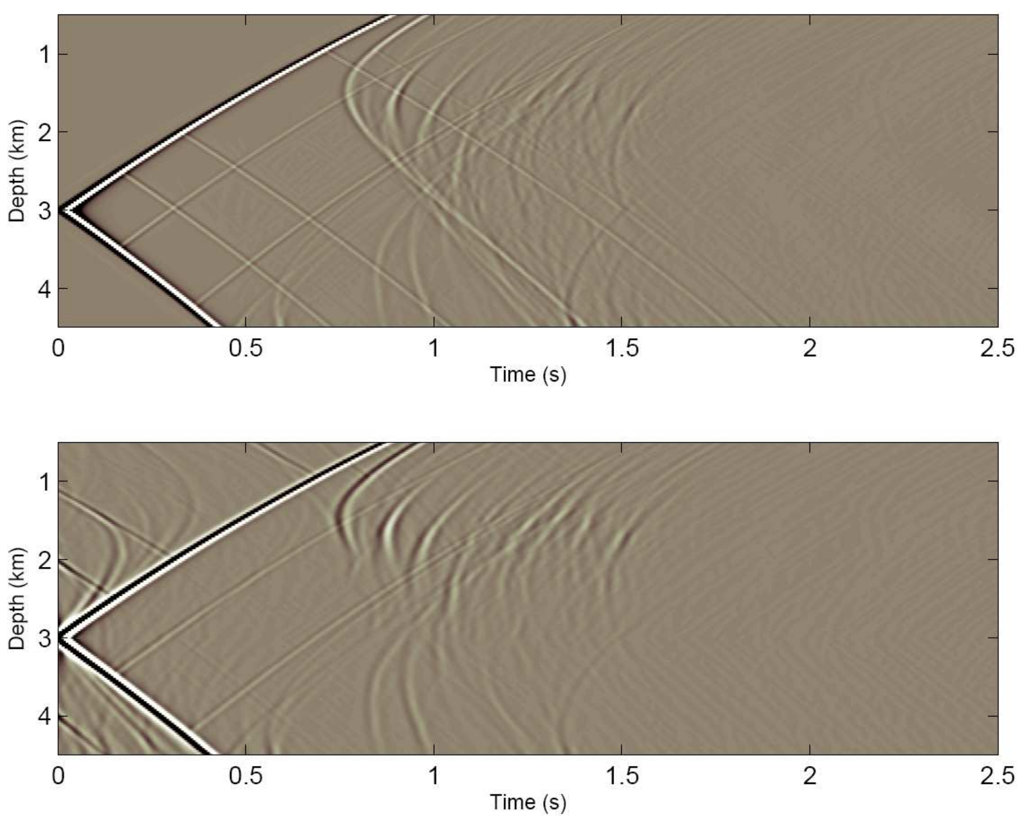


Figure 3: Common down-hole shot gathers (a) obtained by placing a source in the bore hole at 3 km depth, and (b) new (redatummed) gathers using seismic interferometry.

In other geometries and velocity regimes, other solutions are possible. For example, Bakulin and Calvert (2005) successfully capture the reflection energy and imaged horizontal reflectors using a horizontal well.

The final step is accomplished using prestack, reverse-time depth migration. For this step we created migration software that uses the same finite-difference modeling algorithm to back propagate the seismic data and an analytic expression for a linear $v(z)$ gradient media to compute the travel times for the forward modeled shot. The back propagation step is performed by injecting each new (redatummed) shot gather, reversed in time, into a finite-difference modeling code at the appropriate depth locations of the new (redatummed) receiver locations. Since our background velocity medium is a simple, linear $v(z)$ gradient, the forward extrapolation of the shot is performed by analytically computing the travel times which are stored in a single travel time table for each new (redatummed) shot location. The migrated image is constructed by extracting and accumulating the time and depth coincident values of the forward and back propagated wavefields.

As for all migration algorithms, we need a generalized migration velocity model. In this case, only the background medium between the salt flank and the borehole is required. Because the distance to the salt flank from the borehole is much less than from the surface sources, the spatial uncertainly introduced by using only a generalized velocity field may be considerably less significant.

# 4. Results

We now apply our processing methodology outlined above to a synthetic data set created using the simplified Gulf of Mexico salt-dome model of Figure 1. The salt dome has a P-wave velocity of 4480 m/s. The background velocity is described by $v(z) = v_0 + Kz$, where $v_0$ is the velocity of the top layer and $K$ is the velocity gradient. The receivers are placed from a depth of 0.5 km to 4.5 km at 25 m intervals.

Performing the seismic interferometry redatumming procedure described under step 1 in the previous section, we obtain 161 new (redatummed), down-hole, common source gathers. One of these gathers at a depth of 3 km is shown in Figure 3b. For comparison, we show the actual common source gather modeled with the source in the bore hole at 3 km depth. We observe that these common source gathers are very similar.

We observe that in Figure 3b, the three linear down going events coming off of the first arrival are absent in the new (redatummed) traces. These events are the downgoing reflections off of the bottom of the flat laying sediments located at the borehole. The omission of this energy is due to the fact that this energy is not excited by a surface source. An actual down-hole source creates upgoing energy which is reflected back downward. (To be theoretically more complete, if we could put sources underground and all around the edges of the model, we would, in fact, be able to reconstruct these down going reflections. Van Manen et al. (2004) used this exact concept of sources all around the model for efficient simulation of wave propagation.)

In order to prepare the new (redatummed) traces for migration, we muted the anticausal (before zero time) events and everything before the direct arrivals. Also problematic were the strong, late time, reflections off the leftmost, shallow salt edge. After the muting, we applied prestack, reverse-time depth migration (as described in step 2 above) to the new (redatummed), common down-hole source gathers. The velocity model used only the background $v(z)$ medium (without the salt or reflectors). We applied the same processing to the actual down-hole common source gathers and the new (redatummed) common source gathers. Figure 4(a) shows the final image using actual down-hole sources and receivers. Figure 4(b) shows the final image using the new (redatummed) data. Both images show excellent delineation of the salt flank and the illuminated portions of the dipping sediments.

For comparison, we also created migrated images using only the zero-offset traces. This operation is computationally much faster than for the non-zero-offset case. We created the zero-offset traces as in Willis *et al.* (2005, 2006) by performing the sums of appropriate autocorrelations. Figure 5a shows the poststack migrated image from the actual down-hole zero-offset section, while Figure 5b shows the image form the new (redatumed) zero-offset gather. They look very similar, which indicates that we captured the main energy needed to obtain a good image of the salt-dome flank. It is clear that the image from the new (redatummed) non-zero offset data (Fig. 4b) is much superior to that created from the new (redatummed) zero-offset data (Fig. 5b) because it more fully illuminates the salt flank image.

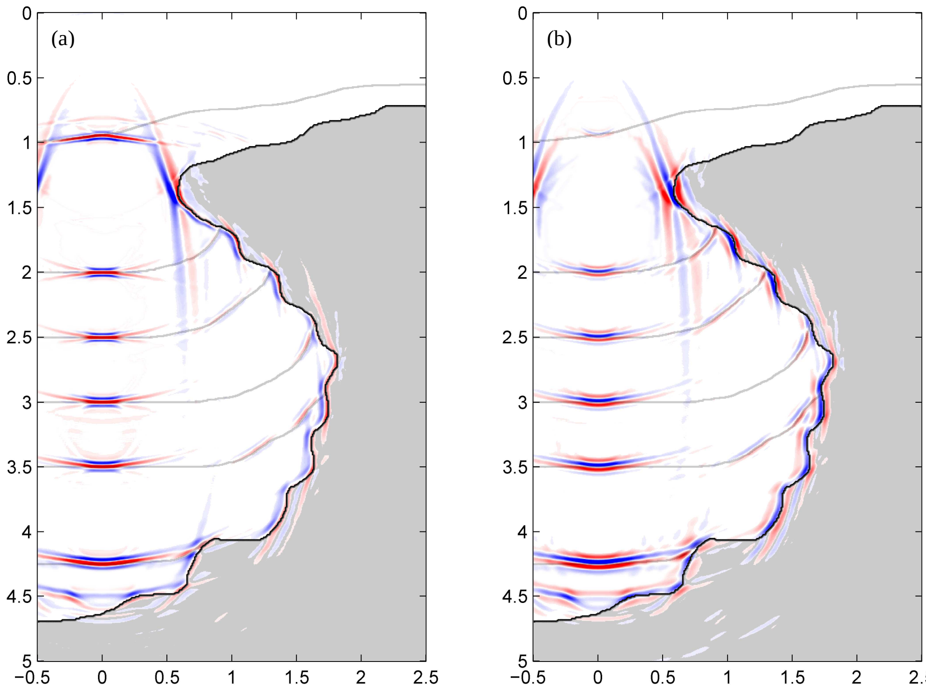


Figure 4: Images using non-zero offset traces of the dipping sediment beds at salt dome flank (a) from reverse time migration of the data created with down-hole sources and receivers (b) from reverse time migration of the redatummed data.

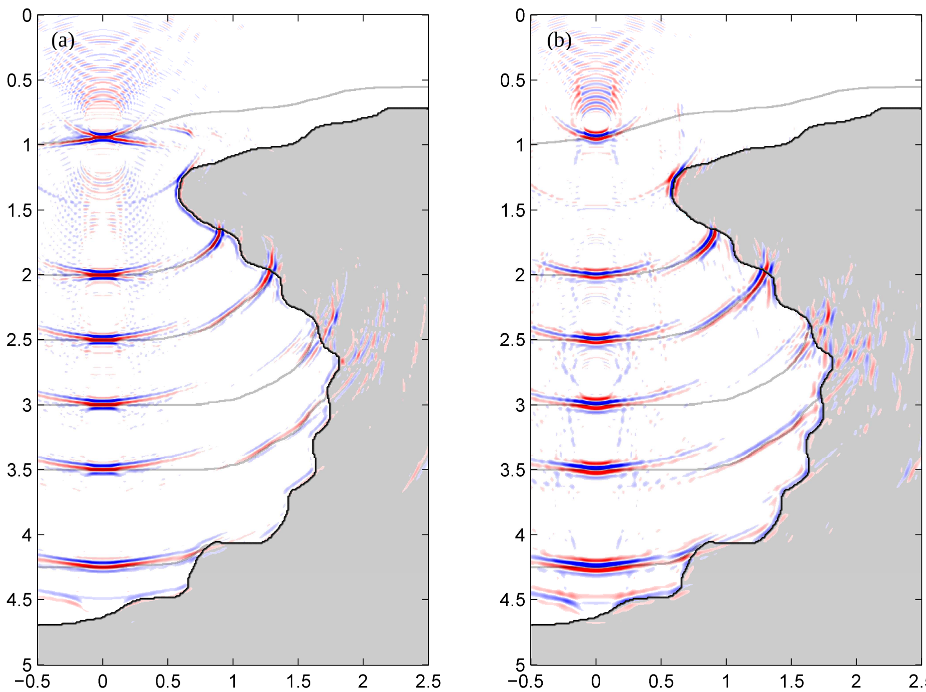


Figure 5: Images using zero offset traces of the dipping sediment beds at salt dome flank (a) from reverse time migration of the data created with down-hole sources and receivers (b) from reverse time migration of the redatummed data.

# 5. Acquisition Aperture

A traditional VSP survey is collected with a very short offset between the surface source and the well head. For a walk along VSP survey, the source is moved along the surface projection of the well trajectory creating a nearly vertical path for seismic energy from the source to the receiver. In order to image more complicated structures, a 3D VSP can be performed where the location of the source is positioned at many offsets and azimuths from the well head. For our walk away VSP application, we need to be able to estimate the farthest distance required for the source to be located so that the turn ray energy will illuminate the underside of the salt flank and reflect back into the borehole receivers. In medium with a constant velocity gradient, the farthest required surface offset from the salt flank can be determined explicitly given a depth and dipping angle of a reflector.

First we examine the requirements for the zero-offset reflection case. In this case the turning ray energy from the source hits the reflector at an angle which is normal to the reflector, and returns along the same ray path (but opposite in direction) back to the receiver. So a single ray path contains the source, receiver and the specular reflection point. The colors in Figure 6 show the required source offset distance (along the surface) to illuminate subsurface reflectors with a range of dips and depths. The top panel in the figure shows the require source offsets for a vertical velocity gradient of 0.4. The bottom panel shows the same information for a very strong velocity gradient of 1.6. The dip angle is defined as an angle between the normal to the reflector and the positive z-axis (pointing downwards) in a clockwise direction. From the figure we can see that: (1) to illuminate the underside of a reflector, such as the overhanging salt dome flank, one need to have a very large source offset, (2) to illuminate the top of a reflector, the required source offset considerable less, and (3) larger velocity gradients require smaller source offsets. Note that these distances also require that the VSP is recorded for the required time length to capture the reflected energy.

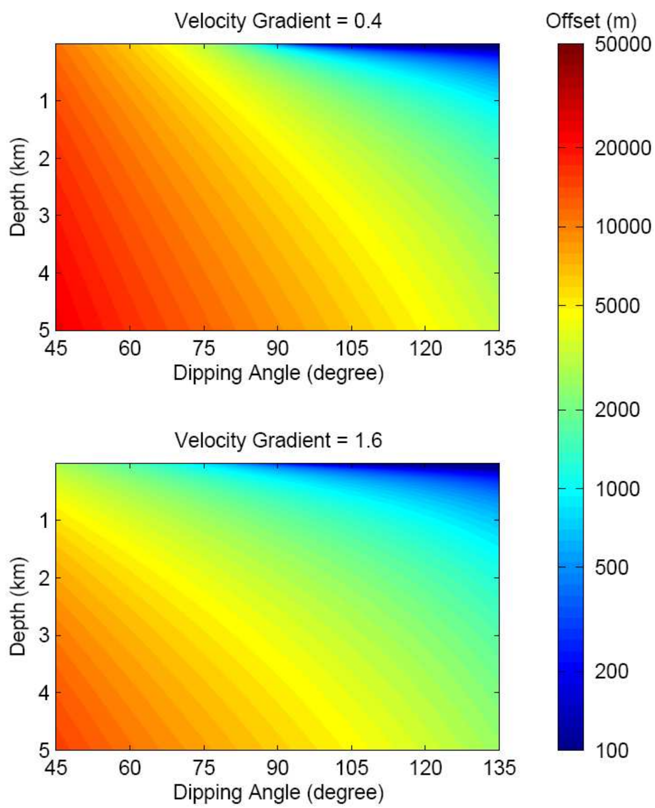


Figure 6: A look-up table showing that for a given background velocity gradient, how far a walk-away VSP survey should go to capture energy that reflected normally off a reflector at given depth and dipping angle.

Next we extend the analysis to the non-zero offset case. For this case, the receivers in the borehole play a significant role in potentially changing the aperture (i.e. source offset distance) required. For this case we are interested in the non-normal specular reflection points on the subsurface reflectors. Figure 7 shows a fan of rays from a single subsurface reflection point. The surface termination points of these rays define all possible source locations which will illuminate this single reflector with a range of incident angles and be captured by the borehole receivers. The rays shown provide information about single bounce reflections and nothing about multiply scattered or reflected energy. A more precise estimation of the acquisition aperture requires performing a full illumination test on a trial expected velocity model. However, this type of modeling can quickly estimate the required offsets and provide intuition about the range of geometries which can be imaged.

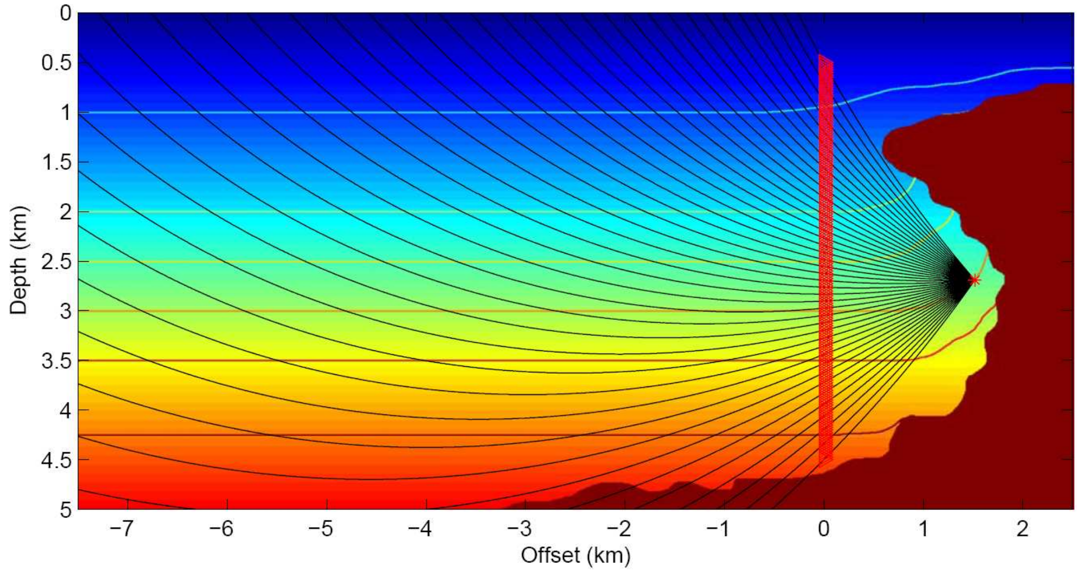


Figure 7: Illustration of the turning rays being reflected off a single point in the subsurface and being captured by receivers in the borehole. The positions where the rays hit the surface (at the top of the model) describe potential locations for surface sources.

# 6. Conclusion

We outline a methodology to accurately image a salt dome flank and upward dipping sediment reflectors using time-reversed acoustics followed by depth migration. By simply correlating and summing traces from a walk away VSP, we move (redatum) the surface sources into the borehole, creating either zero-offset (poststack) or non-zero offset (prestack) traces, which are as if the data were originally collected with down-hole sources and receivers. The zero-offset data can be created in an almost fully automated manner and in near real-time. This approach is of potentially great value to quick turn-around projects or in the field quality control efforts. On the other hand, a sharper image of the salt-dome flank is obtained using the new (redatummed) non-zero offset traces. Our tests show that the new (redatummed) traces create migrated images which are remarkably close to the images from data collected in the borehole. Our preliminary acquisition aperture study gives estimates of the source offset ranges required to collect a walk away VSP which captures the required turning ray energy reflected from the salt flank.

# 7. Acknowledgement

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# Appendix: Reverse Time Migration and TRA

Reverse Time Migration (RTM) is an imaging method, which has been well developed in the literature during the past 20 years (Whitmore, 1983; Baysal et al, 1983; Levin, 1984; Hellman et al, 1986). However, it is important to understand that reverse time migration (RTM) is distinctly different from TRA, although both are built upon the notion of the time symmetric properties of the wave equation. TRA (TRM) is a much more recent development which is only starting to be applied to seismic data, coming from the medical and laboratory environments in the past few years. It is a way of collapsing acoustic energy back to the source location. It does not perform any imaging. It is actually a way of redatumming, or retrofocusing a recorded wavefield back to the original source location.

RTM uses a numerical modeling scheme, such as finite differences or Kirchhoff extrapolation, to implement running the wave equation backward in time and then invokes an imaging condition to create the migrated section. The whole process includes two operations: 1) a wave equation propagation of a recorded wavefield, and 2) an application of an imaging condition. For prestack Reverse Time depth Migration, there are actually two wavefields which are propagated: 1) the recorded shot record which is propagated backward in time, and 2) a synthetic shot record which is propagated forward in time. An imaging condition is applied to corresponding snapshots of these wavefields which amounts to a multiplication (or division) of the back propagated shot record and the forward modeled shot record. The propagation steps are accomplished by finite difference or other numerical modeling techniques. For this method to work at all, the velocity field of the medium is required to be known very well.

On the other hand, TRA is based on not having to know anything about the medium. The velocity of the medium and sometimes even the locations of the receivers are not required. In physical experiments the measured wavefield is reinjected back into the rock/medium and the energy retrofocuses to the source location. In computational analyses, the back propagation is accomplished by invoking reciprocity and performing the appropriate auto and cross correlations. No velocity information is required or used. No modeling software is used. No imaging step is performed. Thus, TRA does not produce an image, but rather a new waveform representing the history of the motion of the medium at that back propagated location.

## References


Bakulin, A. and R. Calvert, 2004, Virtual Source: New Method for Imaging and 4D Below Complex Overburden, 74th Annual International Meeting, SEG, Expanded Abstracts, 2477-2480.

Calvert, R.W., A. Bakulin, and T. C. Jones, 2004, Virtual sources, a new way to remove overburden problems: 66th Annual International Meeting, EAGE, Extended Abstracts, 234.

Derode, A., E. Larose, M. Campillo and M. Fink, 2003, How to estimate the Green's function of a heterogeneous medium between two passive sensors? Application to acoustic waves, Applied Physics Letters, 83(15), 3054-3056.

Fink, M., 1999, Time reversed acoustics, Scientific American, 281, 91-97.

Hornby, B. E., J. Yu, J. A. Sharp, A. Ray, Y. Quist and C. Regone, 2006, VSP: Beyond time-to-depth, The Leading Edge, 25(4), 446-452

Lu, R., X. Campman, M. E. Willis, M. Nafi Toksöz and M. V. de Hoop, 2006, An application of TRA to the pre-and post stack imaging of a salt-dome flank, 68th Annual Meeting, EAGE, Expanded Abstracts

Schuster, G., F. Followill, L. Katz, J. Yu, and Z. Liu, 2003, Autocorrelogram migration: theory: Geophysics 68, 1685–1694

Schuster, G., J. Yu, J. Sheng, and J. Rickett, 2004, Interferometric/daylight seismic imaging: Geophysical Journal International, 157,838–852

Snieder, R., 2004, Extracting the Green’s function from the correlation of coda waves: a derivation based on stationary phase: Physics Review E, 69, 46610.

Van Manen, D. V., J. O. A. Robertson, and A. Curtis, 2005, Modeling of wave propagation in inhomogeneous media, Physical Review Letters, 94:164301.

Wapenaar, C. P. A., 2004, Retrieving the elastodynamic Green’s function of an arbitrary inhomogeneous medium by cross correlation, Physical Review Letters, 93:254301.

Wapenaar, C. P. A., J. T. Fokkema, and R. Snieder, 2005, Retrieving the Green's function in an open system by cross correlation: a comparison of approaches (L), Journal of the Acoustical Society of America, 118(5), 2783-2786.

Wapenaar, C.P.A. and Fokkema, J.T., 2005, Seismic interferometry, time reversal and reciprocity, Extend. Abstr. 67th Ann. Mtg. Eur. Assn. Geosc. Eng., G-031.

Willis, M., R. Lu, D. Burns, M. N. Toksöz, X. Campman, and M. de Hoop, 2005, A Novel Application of Time-Reverse Acoustics: Salt Dome Flank Imaging Using Walk Away VSP Surveys, MIT Earth Resources Laboratory Sponsors Meeting Annual Report.

Willis, M., R. Lu, X. Campman, M. N. Toksöz, Y. Zhang, and M. de Hoop, 2006, A Novel Application of Time-Reverse Acoustics: Salt Dome Flank Imaging Using Walk Away VSP Surveys, Geophysics, 71(2), A7-A11.